PB-222 029

A MATHEMATICAL MODEL FOR AEROBIC DIGESTION

NATIONAL ENVIRONMENTAL RESEARCH CENTER

JULY 1973

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U. S. DEPARTMENT OF COMMERCE

EPA-670/2-73-045
July 1973

PB 222 029

A MATHEMATICAL MODEL FOR AEROBIC DIGESTION

By

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Program Element No. 1B2043

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U.S. ENVIRONMENTAL PROTECTION AGENCY
CINCINNATI, OHIO 45268

BIBLIOGRAPHIC DATA SHEET	1. Report No. EPA-670/2-73-045	2.	3. Recipient's Accession No. PB-222 029
4. Title and Subtitle A MATHEMATICAL MODEL FOR AEROBIC DIGESTION			5. Report Date 1973-issuing date
			6.
7. Author(s) R. Smith, R. G. Eilers, and E. D. Hall			8. Performing Organization Rept. No.
9. Performing Organization Name and Address U.S. Environmental Protection Agency National Environmental Research Center Office of Research & Development Cincinnati, Ohio 45268			10. Project/Task/Work Unit No.
			11. Contract/Grant No.
12. Sponsoring Organization Name and Address same			13. Type of Report & Period Covered Final
			14.
15. Supplementary Notes			

16. Abstracts

Design and cost relationships for various modifications of the aerobic digestion process for disposal of waste organic sludges are given. For example, the aerobic digester can be operated on a continuous basis with a settler or on a fill and draw basis. The aerobic digester can be used for reducing the volume of waste activated sludge only or for digesting a combination of primary and waste activated sludge. The concentration of other constituents such as phosphorus and nitrogen in the effluent streams is also calculated.

17. Key Words and Document Analysis. 17a. Descriptors

Sludge disposal, Sludge digestion, Sewage treatment, Biodegradability

17b. Identifiers/Open-Ended Terms

Sludge treatment, Sewage sludge, Municipal wastes, Biological treatment, Aerobic digestion, Waste activated sludge

17c. COSATI Field/Group 13B

18. Availability Statement	19. Security Class (This Report)	21. No. of Pages
Release to public	UNCLASSIFIED	50
	20. Security Class (This Page) UNCLASSIFIED	22. Price $3.75

FORM NTIS-35 (REV. 3-72) THIS FORM MAY BE REPRODUCED USCOMM-DC 14952-P72

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FOREWORD

Man and his environment must be protected from the adverse effects of pesticides, radiation, noise and other forms of pollution, and the unwise management of solid waste. Efforts to protect the environment require a focus that recognizes the interplay between the components of our physical environment--air, water, and land. The National Environmental Research Centers provide this multidisciplinary focus through programs engaged in

- studies on the effects of environmental contaminants on man and the biosphere, and
- a search for ways to prevent contamination and to recycle valuable resources.

As part of these activities, the study described here examines the design and cost relationships for various modifications of the aerobic digestion process for disposal of waste organic sludges.

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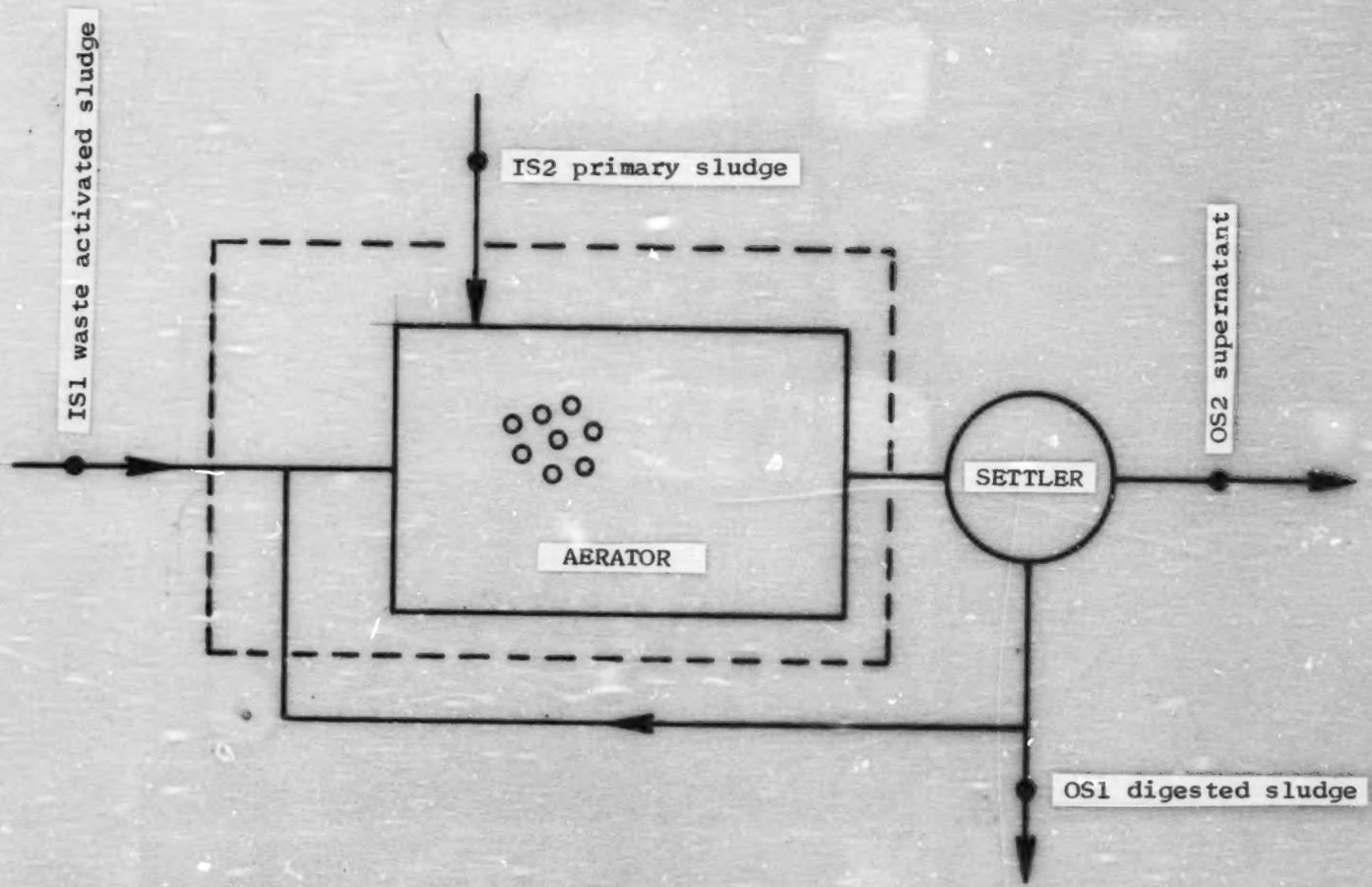
ABSTRACT

Design and cost relationships for various modifications of the aerobic digestion process for disposal of waste organic sludges are given. For example, the aerobic digester can be operated on a continous basis with a settler or on a fill and draw basis. The aerobic digester can be used for reducing the volume of waste activated sludge only or for digesting a combination of primary and waste activated sludge. The concentration of other constituents such as phosphorus and nitrogen in the effluent streams is also calculated.

A MATHEMATICAL MODEL FOR AEROBIC DIGESTION

Aerobic digestion of organic sludges from municipal wastewater treatment has been gaining in popularity over anaerobic digestion in recent years. The reasons for this are believed to be the relative simplicity of aerobic digestion in terms of fewer required controls, less probability of upset, and simpler operation. Although the physical and biological principles involved in aerobic digestion are well known, design relationships are not well established in terms of the capacity of equipment and structures for a specified degree of treatment with a known feed stream. This can be seen from the following discussion of the assumptions made in development of a model for aerobic digestion. A sketch of the process is shown in Figure 1.

First, it should be pointed out that several operational alternatives are available in designing the process. For example, the process can be designed to handle waste activated sludge or trickling filter humus alone. When a primary settler is provided, the primary sludge can also be added to the aerobic digester and stabilized. In the larger plants it is common practice to follow the aerator with a settler which separates the solids from the supernatant and returns the solids to the aerator. The supernatant is commonly returned to the main plant. The aerobically digested sludge is often disposed of on the land either directly or by first dewatering on sand drying beds. Centrifuges or air flotation can be used to thicken aerobically digested sludge.



AEROBIC DIGESTER DIAGRAM

Figure 1

In smaller plants, say less than 1 mgd, sludge is fed to the digester once a day and perhaps once or twice a week the air supply is shut off and the sludge is allowed to settle before the supernatant is drawn off and returned to the plant. This decanting operation occupies about 1-1½ hrs. When the sludge concentration in the digester reaches a level which precludes effective settling, (2-3% for WAS and 4% for combined sludges), a portion of the sludge is drawn off thus reducing the liquid level in the digester. If the sludge is not fully digested it is sometimes necessary to aerate the digester contents for as much as 5 days with no feeding to achieve a well digested sludge.

The basic design variable for the aerator is either detention time (aerator volume/average influent flow volume) or sludge retention time (aerator volume/average sludge wasting rate). The aerator is sometimes sized using pounds of volatile solids fed per day per 1000 cu. ft. of aerator capacity as the principal design variable.

Several laboratory studies have been made to relate the percent volatile suspended solids destruction to detention time or SRT. The best known and most widely quoted data of this sort is reported by Jaworski, Lawton, and Rohlich.[1] This data is shown plotted on semi-log paper in Figure 2. Clearly, one of the most fundamental problems in using this kind of data is to estimate the fraction of the volatile solids which are essentially non-biodegradable. Another and related problem is to estimate the shape of the curves shown in Figure 2 when the mix of primary and waste activated sludge is varied or when the character of the WAS is varied. Information which would allow for this kind of design is not available. The data shown in Figure 2 is for a mixture of primary and waste activated sludge in

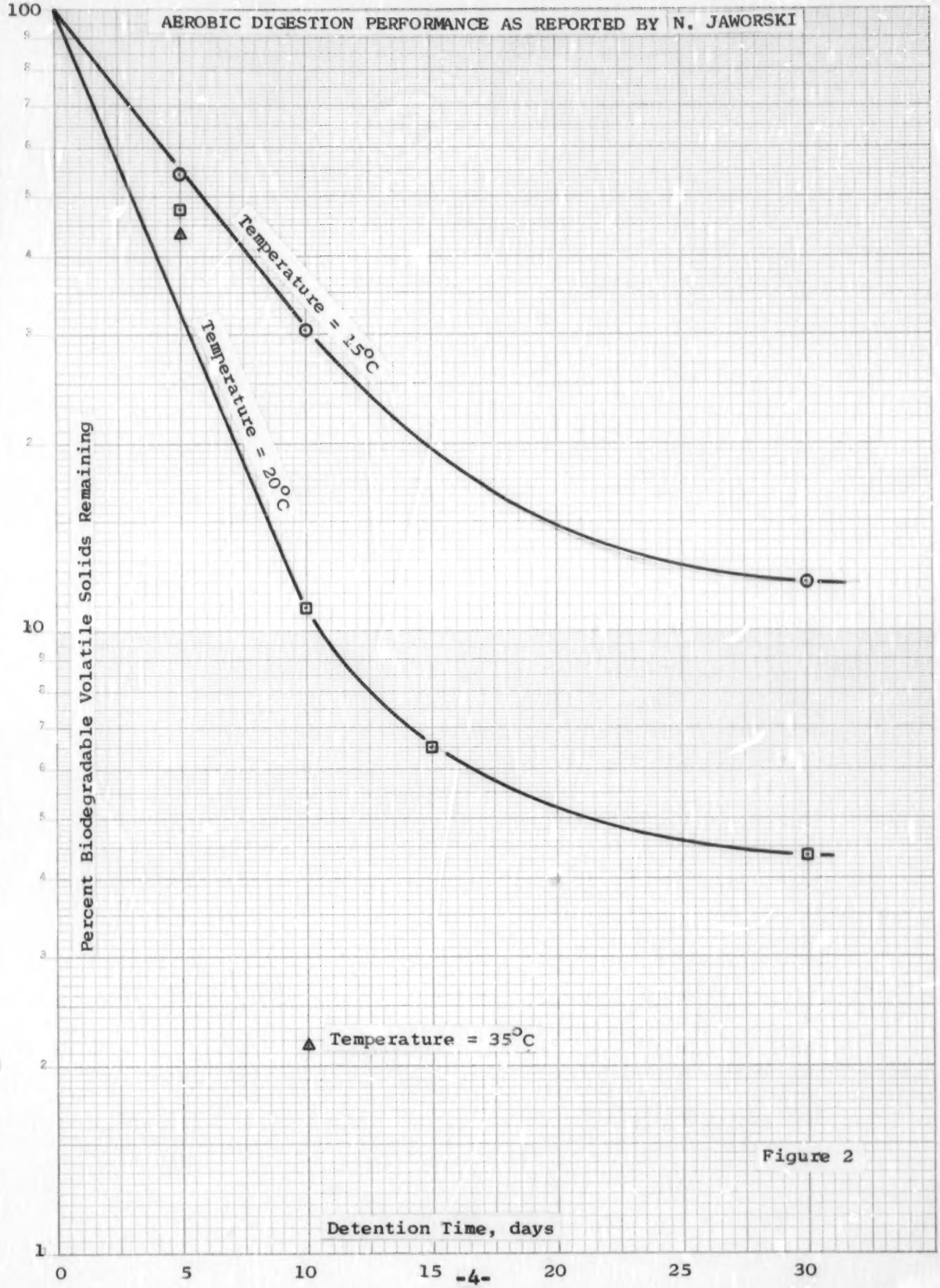

AEROBIC DIGESTION PERFORMANCE AS REPORTED BY N. JAWORSKI
Percent Biodegradable Volatile Solids Remaining
Temperature = 15°C
Temperature = 20°C
Temperature = 35°C
Detention Time, days
100
10
1
0
5
10
15
20
25
30

Figure 2

the proportions of 1.75 primary to 1.0 WAS. Therefore, we see that even with this mix, where primary sludge represents the greater proportion, the digestion process is almost complete after 15 days when the temperature is 20°C. When the temperature is 15°C on the other hand, about 10% of the biodegradable volatile suspended solids remains at 30 days of detention time.

A brief examination of the comparison between existing theory and selected experimental results is given in the Appendix. A computer program, also discussed in the Appendix, has been developed to simulate the design and operation of an aerobic digester with no settler where both primary and waste activated sludge is fed and wasting of supernatant and digested sludge is carried out periodically.

Therefore, it will be assumed here that for aerobic digestion of waste activated sludge or trickling filter humus alone, the aerator will be sized for 10-15 days of detention time. When primary sludge is added to the aerobic digester, the digester will be sized for 20-30 days of detention time.

The stream vector used in the Executive program identifies solid and liquid pollutants as organic or inorganic and breaks up the organic or volatile fractions as biodegradable or non-biodegradable. The stream vector used is shown in Figure 3. Consider the waste activated sludge stream first. The number of this stream is IS1 standing for Input Stream No. 1. The solids wasted from the aerator of the activated sludge process are classified as MLASS, active solids, MLBSS, biodegradable volatile solids, MLNBSS, volatile non-biodegradable solids, MLDSS, volatile debris solids, and MLISS, inorganic solids. To compute the fraction of the volatile solids which are not degraded in the aerobic digester, the assumptions contained in EPA Report WP-20-9[2] will be used.

CONTENTS OF STREAM MATRIX (SMATX)

(I designates the stream number)

Row No.	Descriptive Parameters	FORTRAN Variable Names
1	Stream Number	SMATX(1,I), I
2	Volume Flow, mgd	SMATX(2,I), Q
3	Solid Organic Carbon, mg/l	SMATX(3,I), SOC
4	Solid Nonbiodegradable Carbon, mg/l	SMATX(4,I), SNBC
5	Solid Organic Nitrogen, mg/l	SMATX(5,I), SON
6	Solid Organic Phosphorus, mg/l	SMATX(6,I), SOP
7	Solid Fixed Matter, mg/l	SMATX(7,I), SFM
8	Solid BOD, mg/l	SMATX(8,I), SBOD
9	Volatile Suspended Solids, mg/l	SMATX(9,I), VSS
10	Total Suspended Solids, mg/l	SMATX(10,I), TSS
11	Dissolved Organic Carbon, mg/l	SMATX(11,I), DOC
12	Dissolved Nonbiodegradable Carbon, mg/l	SMATX(12,I), DNBC
13	Dissolved Nitrogen, mg/l	SMATX(13,I), DN
14	Dissolved Phosphorus, mg/l	SMATX(14,I), DP
15	Dissolved Fixed Matter, mg/l	SMATX(15,I), DFM
16	Alkalinity, mg/l	SMATX(16,I), ALK
17	Dissolved BOD, mg/l	SMATX(17,I), DBOD
18	Unassigned	
19	Unassigned	
20	Unassigned	

Figure 3

From this report (WP-20-9) the ratio of BOD/VSS is 0.84 for active solids. The yield coefficient representing the production of active solids from biodegradable volatile solids is 0.65. The fraction of active solids remaining after cell lysis is 0.18. The compaction ratio representing the concentration of solids in the waste stream divided by the mixed liquor suspended solids in the aerator is URSS and this ratio has a value in the range 3-5. The concentration of non-biodegradable suspended solids which enters the aerobic digester from the underflow of the final settler can be computed as follows:

```
SMATX(10,IS1) = URSS*(MLASS*0.18 + MLBSS*0.84*0.65*0.18 + MLNBSS +
MLISS + MLDSS)                                                    (1)
```

The ratio of total organic carbon to volatile suspended solids is 2.13 for primary sludge. Therefore, the concentration of non-biodegradable solids which enter the aerobic digester from the underflow of the primary settler can be computed as follows:

```
SMATX(10,IS2) = SMATX(4,IS2)*2.13 + (SMATX(8,IS2) + SMATX(17,IS2))
*0.65*0.18 + SMATX(7,IS2)                                         (2)
```

In equations (1) and (2) the inorganic solids are represented by MLISS and SMATX(7,IS2). Therefore, the percent volatile can be computed for entering and leaving sludge.

The use of these equations can be best illustrated with an example. For example, consider a 1 mgd plant with a raw BOD concentration of 200 mg/l and a suspended solids concentration of 200 mg/l. Assume that the suspended solids in the raw stream are 85% volatile and that 65% of the volatiles are biodegradable. Assume that the primary settler removes 50% of the suspended solids and 35% of the BOD. The

amount of sludge in the underflow stream of the primary settler is, therefore, 833 lb/day. The volatile solids in the underflow is 708 lb/day and the amount of biodegradable volatile solids is 460 lb/day. Thus, 125 lb. of non-volatile solids are produced and 248 lb/day of volatile non-biodegradable solids are produced. The 460 lb/day of volatile biodegradable solids produced will reduce to 45 lb/day when completely degraded in the aerobic digester. The multiplier is 0.84 to convert to BOD times 0.65 for the yield coefficient times 0.18 to convert to debris solids remaining. Thus, a total of 418 lb/day of primary solids will remain after aerobic digestion.

To compute the residual solids from the waste activated sludge process, it will be necessary to refer to the example given in EPA Report WP-20-9. Here the active solids, MLASS were computed as 756 mg/l. The biodegradable solids MLBSS were computed as 288 mg/l, the non biodegradable solids, MLNBSS as 624 mg/l, the debris solids, MLDSS as 48 mg/l, and the inorganic solids as 284 mg/l for a total of 2000 mg/l.

The amounts of remaining solids, after aerobic digestion, are computed in Figure 4. To summarize, in a 1 mgd plant, about 1806 pounds of solids are produced per day and after aerobic digestion, this is reduced to about 963 lb/day. These computed reductions in total suspended solids and volatile suspended solids are similar to those reported in the literature. Clearly, the percent reduction which can be achieved will depend on the character of the sludges produced. Because of the inherent difficulty in identifying the fraction of

MASS BALANCE FOR AEROBIC DIGESTION OF COMBINED PRIMARY AND WASTE ACTIVATED SLUDGE

I. PRIMARY SLUDGE 833 lb/day	
1. non-volatile, 833 x .15 =	125 lb/day
2. volatile, 833 x .85 = 708 lb/day	
a. non-biodegradable, 708 x .35 =	248 lb/day
b. biodegradable, 708 x .65 = 460 lb/day	
debris solids, 460 x .84 x .65 x .18 =	45 lb/day
	418 lb/day
II. WASTE ACTIVATED SLUDGE 973 lb/day	
1. non-volatile, MLISS, 284 x 5 x .0117 x 8.33 =	138 lb/day
2. volatile, 1716 x 5 x .0117 x 8.33 = 835 lb/day	
a. MLASS, 756 x .18 x 5 x .0117 =	66 lb/day
b. MLBSS, 288 x .84 x .65 x .18 x 5 x .0117 x 8.33 =	14 lb/day
c. MLDSS, 48 x 5 x .0117 x 8.33 =	23 lb/day
d. MLNBSS, 624 x 5 x .0117 x 8.33 =	304 lb/day
	545 lb/day
TOTAL AMOUNT OF SLUDGE FROM AEROBIC DIGESTER	963 lb/day
Reduction in Sludge Solids	47%
Reduction in Volatile Sludge Solids	54%

Figure 4

the sludge which is biodegradable, the assumption that all of the biodegradable material is degraded in 10 days for waste activated sludge alone and 20 days for combined waste activated sludge and primary sludge seems justified.

To continue with the example, assume that the concentration of primary sludge is 5% and that the concentration of waste activated sludge is 1.0%. The volume of the primary sludge stream will, therefore, be .002 mgd and the volume of the waste activated sludge stream will be .0117 mgd. If we allow 20 days of detention time, the size of the aerator will be 36,631 cu. ft. If the aerator had been designed to handle waste activated sludge only, the size of the aerator would have been 15,642 cu. ft. Another design relationship which is used by one of the principal suppliers of aerobic digesters is 0.05 lb/day/cu. ft. of aerator. Since the total mass flow to the aerator will be 1806 lb/day, the size of the aerator will be 36,120 cu. ft. For waste activated sludge only, the size of the aerator would have been 16,700 cu. ft. When detention time is used, the importance of thickening the waste activated sludge as much as possible before aerobic digestion can be seen. This also emphasizes the lack of certainty about the proper method of sizing the aerator. In the model, the aerator volume is computed in both ways and the greater volume is taken.

When a final settler is provided, the settler will be sized on overflow rate. Recommended overflow rates are in the range 100-150 gpd/sq. ft. In the example given above, the size of the settler, based on 100 gpd/sq. ft., will be 137 sq. ft. The diameter of a circular settler for the 1 mgd size would be 13 ft.

Diffused air seems to be the preferred method of supplying oxygen to the aerobic digestion process. This is to avoid problems with changing liquid level in the aerator. The minimum amount of air suggested to keep the solids in suspension is 20 scf/1000 cu. ft. of aerator capacity. Thus, if we size the aerator at 36,631 cu. ft. the air supply would be 733 scfm. We can also estimate the oxygen requirements from the data in Figure 4. The COD of raw sewage is about 1.5 times the volatile solids and the COD of active solids is about 1.42 times the active solids. From Figure 3 we can see that 460 lb/day of biodegradable volatile solids originate in the primary sludge and about 140 lb/day of volatile biodegradable solids, and 368 lb. of active solids originate in the aerator of the activated sludge process. Multiplying these amounts by the factors given above an oxygen requirement of 1423 lb. O_2 per day is computed. Nitrification of ammonia nitrogen is also likely to occur in the aerobic digester and this will also demand oxygen. Assume that the concentration of ammonia nitrogen in the influent sludge streams is 20 mg/l. Nitrogen will also be released when the sludge solids are destroyed. Organic material is normally about 7.5 % nitrogen. Therefore, if 82% of the biodegradable volatile solids are destroyed, a total of 60 pounds of nitrogen will be solubilized. The ammonia nitrogen entering with the sludge streams represents only about 1.9 lb/day. About 4.6 pounds of oxygen is required for each pound of ammonia nitrogen converted to nitrate. Therefore, an additional 285 lb/day of oxygen will be required to convert the nitrogen to nitrate. The total oxygen demand is therefore, 1708 lb/day. If we assume an

aeration efficiency of 5%, the air blowers must supply 1708/.075/.232/.05/1440 = 1363 scfm. For the large aerator with 35,631 cu. ft. this is more than that required to keep the sludge in suspension. In the model, the required blower size is computed in both ways and the cost is based on the larger value.

Phosphorus must also be conserved around the aerobic digester and since organic material is about 1% phosphorus, the phosphorus released, as a result of destruction of organics, is assumed to appear in the supernatant stream.

The amount of sludge recycle pumping capacity can, theoretically, be determined by writing a mass balance around the control volume shown in Figure 1 by the dashed rectangle. Let Q equal the volume flow (mgd) of the sum of the primary and waste activated sludge streams. Let Q_r equal the volume of the return stream. Let VSS equal the volatile suspended concentration of the feed stream and let MLVSS equal the concentration of volatile solids in the aerator. Let F_r equal the fraction of the influent volatile suspended solids which are destroyed in the aerator. URSS stands for the compaction ratio in the settler. The following mass balance equation can now be written:

$$Q*VSS + Q_r*MLVSS*URSS = (Q+Q_r)*MLVSS + F_r*Q*VSS$$

Solving for the ratio Q_r/Q, we find the following result:

$$Q_r/Q = \frac{1 - (VSS/MLVSS)*(1-F_r)}{URSS - 1}$$

If we use the same example, the concentration of volatile suspended solids in the feed stream will be 1.36%. If we take MLVSS to be 2% and URSS to be 1.5, the ratio Q_r/Q is 1.32. Because of the uncertainties involved in making this computation, the return pumps will be sized as 1.5 times the sum of the influent streams.

In developing a model for aerobic digestion, it is necessary to estimate the character of both the sludge stream (OS1) and the supernatant stream from the aerobic digester. Measurements of this kind are not readily available in the literature. Preliminary results from Hollywood, Florida show that when primary sludge alone is aerobically digested, the concentration of solids in the aerator will build up to about 5% and this is suitable for direct application to the land. Preliminary results from the Metro Denver plant suggest that the suspended solids in the supernatant is about 150 mg/l when waste activated sludge only is aerobically digested. Jaworski studied the aerobic digestion of combined primary and waste activated sludge and found the BOD of the supernatant to be generally less than 100 mg/l with a COD in the range 360-670. mg/l.

Based on this paucity of information, it will be assumed in the model that the supernatant stream has a total BOD of 100 mg/l and a dissolved BOD of 50 mg/l. The suspended solids in the supernatant will be taken as 200 mg/l and the percent volatile will be computed from the remaining nonbiodegradable solids balance.

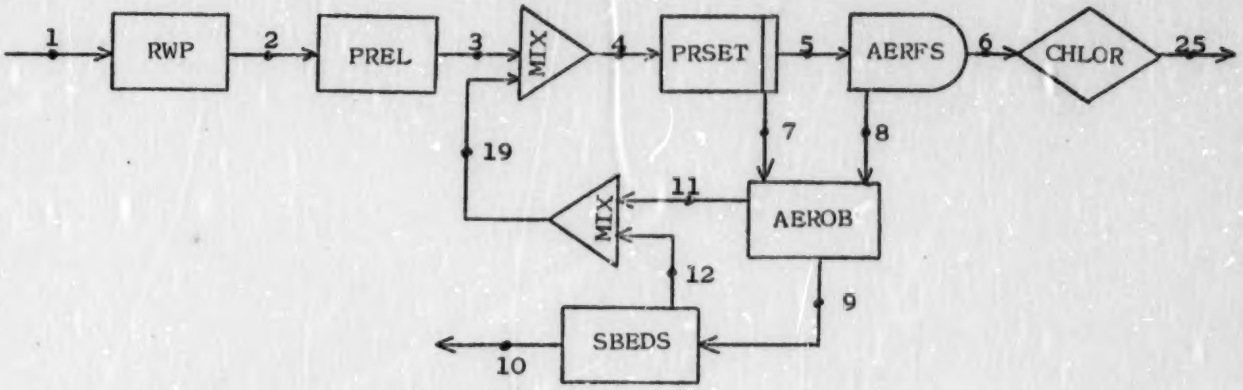
The concentration of solids in the sludge stream from the aerobic digester will be taken as 4% when a combination of primary and waste activated sludge is used and 2.5% when waste activated sludge alone is treated.

The aerobic digestion computer model was written in FORTRAN and is used as a subroutine in the "Executive Digital Computer Program for Preliminary Design of Wastewater Treatment Systems."[12] This Executive Program is used to simulate the performance and cost of any wastewater treatment system composed of unit processes arranged in specific system configurations. The aerobic digestion model is used as one of the unit process models in the Executive Program.

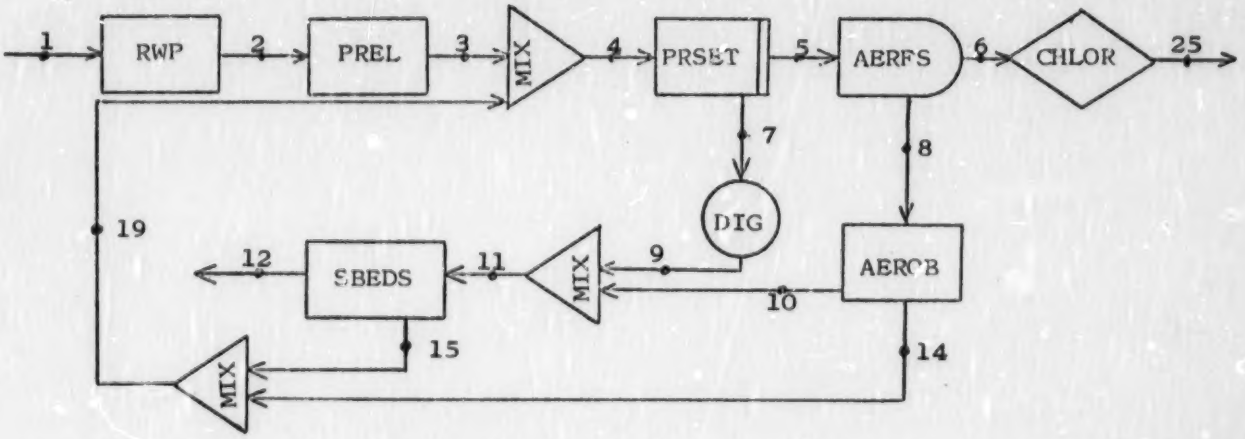
The Executive Program has been used to investigate the cost of sludge digestion by simulating the three wastewater treatment systems pictured in Figure 5. System 1 consists of raw wastewater pumping (RWP), preliminary treatment (PREL), primary sedimentation (PRSET), aeration-final sedimentation (AERFS), chlorination (CHLOR), aerobic digestion (AEROB), and sludge drying beds (SBEDS). MIX and SPLIT on the diagrams represent stream mixers and splitters. System 1 treats combined primary sludge (PS) and waste activated sludge (WAS) by means of aerobic digestion. System 2 is similar to System 1 except that PS is treated with anaerobic digestion (DIG) and WAS is treated by aerobic digestion. Note that Systems 1 and 2 can substitute vacuum filtration (VACF) and multiple hearth incineration (MHINC) in place of sludge drying beds for sludge disposal as is done in System 3. System 3 mixes PS and WAS and treats the combined sludge with anaerobic digestion.

Detention time for the aerator of AEROB was 30 days for the 1 mgd size plant of System 1 and 20 days for the 10 and 100 mgd plants. For System 2, 15 days detention time was used for the 1 mgd plant

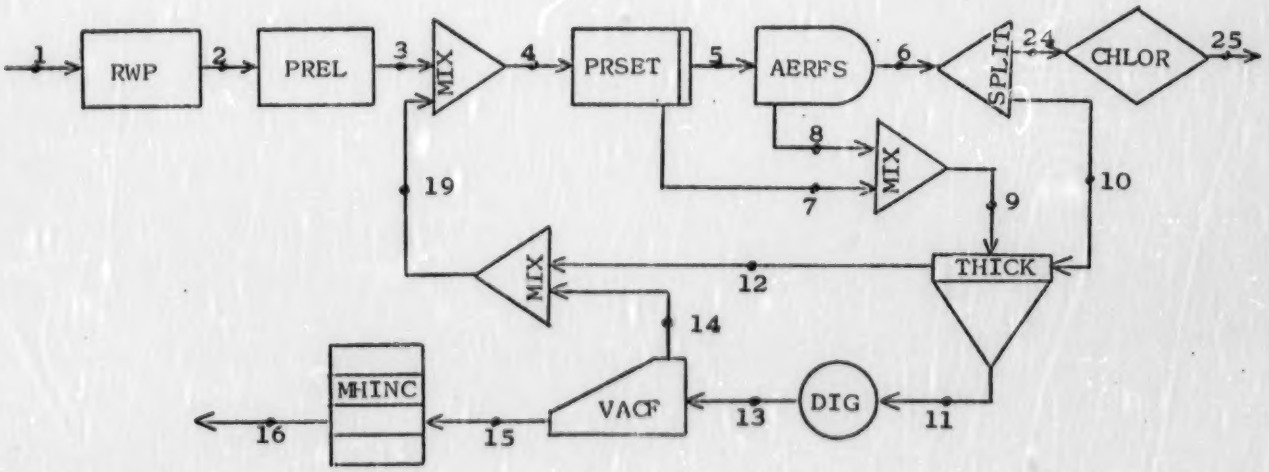
TREATMENT PLANT SYSTEMS USING
AEROBIC AND ANAEROBIC DIGESTION OF
PRIMARY AND WASTE ACTIVATED SLUDGES



SYSTEM 1



SYSTEM 2



SYSTEM 3

Figure 5

and 10 days for the 10 and 100 mgd plants. No final settler or sludge return pumps are used with the aerobic digestion process at the 1 mgd plant size, but they are included in the 10 and 100 mgd plants. The total suspended solids concentration of the sludge stream out of AEROB is assumed to be 25,000 mg/l for WAS and 40,000 mg/l for combined PS and WAS. Electrical power cost was taken to be 1.6 cents per killowatt hour at the 1 mgd plant size, 1.3 ¢/kwhr at 10 mgd, and 1.1 ¢/kwhr at 100 mgd.

Based on previous results, it was concluded that it is generally preferable to use sludge drying beds for activated sludge plants of size 10 mgd or less. At sizes greater than 10 mgd, vacuum filtration and multiple hearth incineration for sludge disposal are often preferred. Therefore, System 1 was evaluated with SBEDS at 1 and 10 mgd and with VACF and MHINC at 10 and 100 mgd. A similar analysis was performed on Systems 2 and 3. The results of these computer runs are given in Tables 1 and 2.

The source card listing of the aerobic digestion subroutine (AEROB) of the Executive Program and a sample program printout follow Table 3, which contains a list of the input parameters (DMATX) to AEROB and the output parameters (OMATX) calculated by the subroutine.

COST OF ACTIVATED SLUDGE PLANTS
with
AEROBIC DIGESTION AND ANAEROBIC DIGESTION

Mgd	SYSTEM 1 WAS + PS Mixed	SYSTEM 2 WAS/AEROB + PS/DIG	SYSTEM 3 THICK + DIG
1(SBEDS)	803,334	879,969	851,670
	19.790	19.377	17.294
	37.007	38.236	35.547
10(SBEDS)	3,501,874	3,247,906	3,031,852
	7.472	6.581	5.572
	14.977	13.542	12.070
10(MHINC)	4,701,037	4,548,705	4,552,543
	8.318	7.420	6.411
	18.393	17.169	16.168
100(MHINC)	29,513,380	27,493,612	29,005,940
	4.745	4.014	3.431
	11.071	9.907	9.647

Capital Cost is in dollars (January 1971)
Operation and Maintenance Cost is in cents/1000 gallons
Total Treatment Cost is in cents/1000 gallons

WAS + PS Mixed: waste activated sludge and primary sludge are both treated by aerobic digestion

WAS/AEROB + PS/DIG: waste activated sludge is treated by aerobic digestion and primary sludge is treated by anaerobic digestion

THICK + DIG: waste activated sludge and primary sludge are mixed followed by gravity sludge thickening and anaerobic digestion

Table 1

COST OF SLUDGE DIGESTION ONLY

Mgd	SYSTEM 1 WAS + PS Mixed	SYSTEM 2 WAS/AEROB	SYSTEM 2 PS/DIG	SYSTEM 2 WAS/AEROB + PS/DIG	SYSTEM 3 THICK + DIG
1(SBEDS)	213,878	126,755	160,337	287,092	231,756
	4.128	2.522	1.212	3.734	1.495
	8.711	5.239	4.648	9.887	6.463
10(SBEDS)	1,197,467	687,588	201,526	889,114	479,324
	2.322	1.282	.170	1.452	.361
	4.887	2.756	.602	3.358	1.388
10(MHINC)	1,194,327	685,834	200,746	886,580	477,961
	2.321	1.362	.170	1.532	.362
	4.880	2.752	.601	3.353	1.386
100(MHINC)	8,587,326	4,443,234	698,444	5,141,678	2,975,030
	1.513	.754	.048	.802	.178
	3.352	1.705	.197	1.902	.815

Capital Cost is in dollars (January 1971)
Operation and Maintenance Cost is in cents/1000 gallons
Total Treatment Cost is in cents/1000 gallons

WAS + PS Mixed: waste activated sludge and primary sludge are both treated by aerobic digestion
WAS/AEROB: waste activated sludge is treated by aerobic digestion
PS/DIG: primary sludge is treated by anaerobic digestion
WAS/AEROB + PS/DIG: the sum of WAS/AEROB and PS/DIG
THICK + DIG: waste activated sludge and primary sludge are mixed followed by gravity sludge thickening and anaerobic digestion

Table 2

EXECUTIVE PROGRAM
AEROBIC DIGESTION SUBROUTINE (AEROB)
DECISION AND OUTPUT MATRIX VARIABLES

DMATX

DMATX(1,N) = XL, program control: this input variable is set equal to the process number (N) given to the aeration (AERFS) process to allow the AEROB subroutine to use output parameters calculated in the aeration process

DMATX(2,N) = XAFS, program control: 0 = no final settler and sludge return pumps are required,
1 = a final settler and sludge return pumps are required with the aerobic digestion process

DMATX(3,N) = DTA, detention time for the aeration, days

DMATX(4,N) = TSS1, total suspended solids in OS1, mg/l

DMATX(5,N) = TSS2, total suspended solids in OS2, mg/l

DMATX(6,N) = BOD2, 5-day BOD concentration in OS2, mg/l

DMATX(7,N) = GSS, overflow rate for the final sedimentation, gpd/sq ft

DMATX(8,N) = HEAD, pumping head of the sludge return pumps, feet

DMATX(13,N) = ECF, excess capacity factor (final settler)

DMATX(14,N) = ECF, excess capacity factor (sludge return pumps)

DMATX(15,N) = ECF, excess capacity factor (blowers)

DMATX(16,N) = ECF, excess capacity factor (aeration tanks)

OMATX

OMATX(1,N) = VAER, volume of the aerator, cu ft/1000

OMATX(2,N) = ACFM, required size of the blower for supplying air to the aerator, cfm

OMATX(3,N) = QPUMP, volume of the return stream flow to the aerator, mgd

OMATX(4,N) = AFS, surface area of the final settler, sq ft/1000

Table 3

```
      SUBROUTINE AEROB
      INTEGER OS1,OS2
      DIMENSION SMAT(20)
      COMMON SMATX(20,25),TMATX(20,25),DMATX(20,20),OMATX(20,20),IP(25),
     . INP,IO,IS1,IS2,OS1,OS2,N,IAERF,CCOST(20,5),COSTO(20,5),
     . ACOST(20,5),TCOST(20,5),DHR,PCT,WPI
      DO 2 I=1,20
    2 SMAT(I)=0.
      IF(IS2) 4,8,4
    4 DO 6 I=1,20
    6 SMAT(I)=SMATX(I,IS2)
    8 L=DMATX(1,N)
      TEMP1=(SMAT(4)*2.13+(SMAT(8)+SMAT(17))*.65*.18)*SMAT(2)
      TEMP2=(OMATX(9,L)*.18+OMATX(10,L)*.0938+OMATX(11,L)+OMATX(12,L))*
     . DMATX(7,L)*SMATX(2,IS1)
      TEMP3=SMAT(7)*SMAT(2)
      TEMP4=OMATX(13,L)*DMATX(7,L)*SMATX(2,IS1)
      SMATX(2,OS1)=((TEMP1+TEMP2+TEMP3+TEMP4)-(SMATX(2,IS1)+
     . SMAT(2))*DMATX(5,N))/(DMATX(4,N)-DMATX(5,N))
      SMATX(2,OS2)=SMATX(2,IS1)+SMAT(2)-SMATX(2,OS1)
      VOLPC=(TEMP1+TEMP2)/(TEMP1+TEMP2+TEMP3+TEMP4)
      SMATX(9,OS1)=DMATX(4,N)*VOLPC
      SMATX(7,OS1)=DMATX(4,N)-SMATX(9,OS1)
      SMATX(3,OS1)=SMATX(9,OS1)/2.13
      SMATX(4,OS1)=SMATX(3,OS1)
      SMATX(5,OS1)=SMATX(3,OS1)/10.
      SMATX(6,OS1)=SMATX(3,OS1)/100.
      SMATX(8,OS1)=0.
      SMATX(10,OS1)=DMATX(4,N)
      SMATX(10,OS2)=DMATX(5,N)
      SMATX(9,OS2)=SMATX(10,OS2)*VOLPC
      SMATX(3,OS2)=SMATX(9,OS2)/2.13
      SMATX(4,OS2)=SMATX(3,OS2)
      SMATX(5,OS2)=SMATX(3,OS2)/10.
      SMATX(6,OS2)=SMATX(3,OS2)/100.
      SMATX(7,OS2)=SMATX(10,OS2)-SMATX(9,OS2)
      SMATX(8,OS2)=50.
      SMATX(11,OS1)=(500.-SMATX(9,OS2)*1.42)/3.2
      SMATX(11,OS2)=SMATX(11,OS1)
      SMATX(12,OS1)=SMATX(11,OS2)/2.
      SMATX(12,OS2)=SMATX(12,OS1)
      ENTN=SMATX(2,IS1)*(SMATX(5,IS1)+SMATX(13,IS1))+SMAT(2)*
     . (SMAT(5)+SMAT(13))
      EXSN=SMATX(2,OS1)*SMATX(5,OS1)+SMATX(2,OS2)*SMATX(5,OS2)
      SMATX(13,OS1)=(ENTN-EXSN)/(SMATX(2,OS1)+SMATX(2,OS2))
      SMATX(13,OS2)=SMATX(13,OS1)
      ENTP=SMATX(2,IS1)*(SMATX(6,IS1)+SMATX(14,IS1))+SMAT(2)*
     . (SMAT(6)+SMATX(14,OS2))
      EXSP=SMATX(2,OS1)*SMATX(6,OS1)+SMATX(2,OS2)*SMATX(6,OS2)
      SMATX(14,OS2)=(ENTP-EXSP)/(SMATX(2,OS1)+SMATX(2,OS2))
      SMATX(14,OS1)=SMATX(14,OS2)
      SMATX(15,OS1)=SMATX(15,IS1)
      SMATX(15,OS2)=SMATX(15,IS1)
      SMATX(16,OS1)=300.
      SMATX(16,OS2)=300.
      SMATX(17,OS1)=DMATX(6,N)-50.
      SMATX(17,OS2)=SMATX(17,OS1)
      VAER1=(SMATX(2,IS1)+SMAT(2))*DMATX(3,N)*1000./7.48*DMATX(16,N)
      VAER2=(SMATX(2,IS1)*SMATX(10,IS1)+SMAT(2)*SMAT(10))*
```

```
     . 8.33/.05/1000.*DMATX(16,N)
      IF(VAER1-VAER2) 10,20,20
   10 VAER=VAER2
      GO TO 30
   20 VAER=VAER1
   30 BSIZE=20.*VAER*DMATX(15,N)
      IF(DMATX(2,N)) 34,32,34
   32 AFS=0.
      GO TO 36
   34 AFS=(SMATX(2,IS1)+SMAT(2))*1000./DMATX(7,N)*DMATX(13,N)
   36 DEMO=(SMATX(9,IS1)*SMATX(2,IS1)+SMAT(9)*SMAT(2)-
     . TEMP1-TEMP2)*8.33*1.5
      CFM=DEMO/.075/.232/.05/1440.*DMATX(15,N)
      IF(BSIZE-CFM) 40,50,50
   40 ACFM=CFM
      GO TO 60
   50 ACFM=BSIZE
   60 QPUMP=(SMATX(2,IS1)+SMAT(2))*DMATX(14,N)*1.5
      X=ALOG(VAER)
      CCOST(N,1)=EXP(2.414380+.175682*X+.084742*X**2.-.002670*X**3.)*
     . 1000.
      OHRS=0.
      XMHRS=0.
      TMSU=0.
      COSTO(N,1)=0.
      X=ALOG(ACFM/1000.)
      CCOST(N,2)=EXP(4.145454+.633339*X+.031939*X**2.-.002419*X**3.)*
     . 1000.
      X=ALOG(ACFM/1000./DMATX(15,N))
      IF(ACFM/1000./DMATX(15,N)-1.) 70,80,80
   70 OHRS=850.
      XMHRS=350.
      GO TO 90
   80 OHRS=EXP(6.900586+.323725*X+.059093*X**2.-.004926*X**3.)
      XMHRS=EXP(6.169937+.294853*X+.175999*X**2.-.040947*X**3.+
     . .003300*X**4.)
   90 HP=ACFM/DMATX(15,N)*8.1*144./(33000.*.8)
      XKW=.8*HP
      XKWPY=XKW*24.*365.
      ECOST=XKWPY*DMATX(10,20)
      SCOST=EXP(.621382+.482047*X)*1000.
      TMSU=ECOST+SCOST
      COSTO(N,2)=((OHRS+XMHRS)*DHR*(1.+PCT)+TMSU*WPI)/SMATX(2,1)/3650.
      IF(DMATX(2,N)) 100,310,100
  100 IF(QPUMP-.5) 190,200,200
  190 CCOST(N,3)=20000.
      GO TO 210
  200 X=ALOG(QPUMP)
      CCOST(N,3)=EXP(3.481553+.377485*X+.093349*X**2.-.006222*X**3.)*
     . 1000.
  210 IF(QPUMP/DMATX(14,N)-.7) 220,230,230
  220 OHRS=400.
      XMHRS=250.
      TMSU=200.+(DMATX(8,N)/30.)*400.
      GO TO 240
  230 X=ALOG(QPUMP/DMATX(14,N))
      OHRS=EXP(6.097269+.253066*X-.193659*X**2.+.078201*X**3.-
     . .006680*X**4.)
      XMHRS=EXP(5.911541-.013158*X+.076643*X**2.)
```

```
      E12=EXP(6.799199+.785690*X-.087865*X**2.+.042646*X**3.-
     . .004488*X**4.)*(DMATX(8,N)/30.)
      S12=EXP(5.851743+.301610*X+.197183*X**2.-.017962*X**3.)
      TMSU=E12+S12
  240 COSTO(N,3)=((OHRS+XMHRS)*DHR*(1.+PCT)+TMSU*WPI)/SMATX(2,1)/3650.
      IF(AFS-1.) 250,260,260
  250 CCOST(N,4)=25000.
      GO TO 270
  260 X=ALOG(AFS)
      CCOST(N,4)=EXP(3.716354+.389861*X+.084560*X**2.-.004718*X**3.)*
     . 1000.
  270 IF(AFS/DMATX(13,N)-1.) 280,290,290
  280 OHRS=300.
      XMHRS=150.
      TMSU=125.
      GO TO 300
  290 X=ALOG(AFS/DMATX(13,N))
      OHRS=EXP(5.846565+.254813*X+.113703*X**2.-.010942*X**3.)
      XMHRS=EXP(5.273419+.228329*X+.122646*X**2.-.011672*X**3.)
      TMSU=EXP(5.669881+.750799*X)
  300 COSTO(N,4)=((OHRS+XMHRS)*DHR*(1.+PCT)+TMSU*WPI)/SMATX(2,1)/3650.
  310 OMATX(1,N)=VAER
      OMATX(2,N)=ACFM
      OMATX(3,N)=QPUMP
      OMATX(4,N)=AFS
      RETURN
      END
```

EXECUTIVE
DIGITAL COMPUTER PROGRAM
FOR
PRELIMINARY DESIGN OF WASTEWATER TREATMENT SYSTEMS

BY
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ADVANCED WASTE TREATMENT RESEARCH LABORATORY
CINCINNATI, OHIO

INCINERATION

EXECUTIVE PROGRAM - TEST OF AEROB/WAS & DIG/PS 10 MGD

SYSTEM DIAGRAM
INPUT DATA

K	N	PROCESS	IS1	IS2	OS1	OS2	III
0	1	15 RWP	1	0	2	0	2
0	2	1 PREL	2	0	3	0	2
1	0	4 MIX	3	19	4	0	1
0	3	2 PRSET	4	0	5	7	0
0	4	3 AERFS	5	0	6	8	0
0	5	18 AEROB	8	0	10	14	0
0	6	6 DIG	7	0	9	0	0
0	0	4 MIX	9	10	11	0	0
0	7	7 VACF	11	0	12	15	0
1	0	4 MIX	14	15	19	0	1
0	8	14 MHINC	12	0	13	0	2
0	9	12 CHLOR	6	0	25	0	2
9	0	0	0	0	0	0	0

STREAM CHARACTERISTICS

VOLUME FLOW, MILLIONS OF GALLONS PER DAY
CONCENTRATIONS, MILLIGRAMS PER LITER

S 1.	Q	SCC	SNBC	SON	SOP	SFM	SBCD	VSS
	10.000	105.000	30.000	10.000	2.000	30.000	140.200	223.600
	ALK	DCC	DNBC	DN	DP	DFM	DBCD	TSS
	250.000	43.000	11.000	19.100	4.000	500.000	59.840	253.600
S 2.	Q	SCC	SNBC	SON	SOP	SFM	SBCD	VSS
	10.000	105.000	30.000	10.000	2.000	30.000	140.200	223.600
	ALK	DCC	DNBC	DN	DP	DFM	DBCD	TSS
	250.000	43.000	11.000	19.100	4.000	500.000	59.840	253.600
S 3.	Q	SCC	SNBC	SON	SOP	SFM	SBCD	VSS
	10.000	105.000	30.000	10.000	2.000	30.000	140.200	223.600
	ALK	DCC	DNBC	DN	DP	DFM	DBCD	TSS
	250.000	43.000	11.000	19.100	4.000	500.000	59.840	253.600
S 4.	Q	SCC	SNBC	SON	SOP	SFM	SBCD	VSS
	10.123	104.564	30.479	9.962	1.984	30.248	138.950	222.695
	ALK	DCC	DNBC	DN	DP	DFM	DBCD	TSS
	257.811	43.608	11.374	25.438	4.860	500.000	59.905	252.944
S 5.	Q	SCC	SNBC	SON	SOP	SFM	SBCD	VSS
	10.111	52.347	15.259	4.987	0.993	15.143	69.562	111.487
	ALK	DCC	DNBC	DN	DP	DFM	DBCD	TSS
	257.811	43.608	11.374	25.438	4.860	500.000	59.905	126.630
S 6.	Q	SCC	SNBC	SON	SOP	SFM	SBCD	VSS
	9.996	5.471	2.121	0.818	0.054	1.750	6.581	13.022
	ALK	DCC	DNBC	DN	DP	DFM	DBCD	TSS
	257.811	14.797	11.374	23.349	5.380	500.000	6.400	14.773
S 7.	Q	SCC	SNBC	SON	SOP	SFM	SBCD	VSS
	0.012	41825.820	12191.968	3984.890	793.937	12099.378	55580.046	89078.234
	ALK	DCC	DNBC	DN	DP	DFM	DBCD	TSS
	257.811	43.608	11.374	25.438	4.860	500.000	59.905	101177.609
S 8.	Q	SCC	SNBC	SON	SOP	SFM	SBCD	VSS
	0.114	3696.983	1433.130	552.688	36.969	1182.644	4446.427	8798.818
	ALK	DCC	DNBC	DN	DP	DFM	DBCD	TSS
	257.811	14.797	11.374	23.349	5.380	500.000	6.400	9981.462
S 9.	Q	SCC	SNBC	SON	SOP	SFM	SBCD	VSS
	0.012	12537.076	12191.968	1205.237	240.127	12099.378	645.350	29838.234
	ALK	DCC	DNBC	DN	DP	DFM	DBCD	TSS
	6707.993	126.410	11.374	1832.212	558.669	500.000	215.117	41937.609

S10.	Q	SOC	SNBC	SON	SOP	SFM	SBCD	VSS
	0.021	8846.015	8846.015	884.601	88.460	6157.993	0.000	18842.011
	ALK	DOC	DNBC	DN	DP	DFM	DBOD	TSS
	300.000	89.360	44.680	406.150	25.361	500.000	50.000	25000.003
S11.	Q	SCC	SNBC	SCN	SGP	SFM	SBCD	VSS
	0.033	10222.636	10093.925	1004.186	145.026	8373.898	240.690	22943.175
	ALK	DOC	DNBC	DN	DP	DFM	DBOD	TSS
	2689.933	103.179	32.258	938.015	224.265	500.000	111.582	31317.070
S12.	Q	SCC	SNBC	SCN	SOP	SFM	SBOD	VSS
	0.003	100430.875	99166.375	9865.488	1424.790	82268.203	2364.634	225402.031
	ALK	DOC	DNBC	DN	DP	DFM	DBCD	TSS
	26426.875	1013.668	316.921	9215.408	2203.261	4912.180	1096.226	307670.313
S13.	Q	SOC	SNBC	SON	SOP	SFM	SBOD	VSS
	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
	ALK	DOC	DNBC	DN	DP	DFM	DBOD	TSS
	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
S14.	Q	SOC	SNBC	SON	SOP	SFM	SBOD	VSS
	0.093	70.768	70.768	7.076	0.707	49.263	50.000	150.736
	ALK	DOC	DNBC	DN	DP	DFM	DBCD	TSS
	300.000	89.360	44.680	406.150	25.361	500.000	50.000	200.000
S15.	Q	SOC	SNBC	SON	SOP	SFM	SBOD	VSS
	0.030	65.284	64.462	6.413	0.926	53.478	1.537	146.521
	ALK	DOC	DNBC	DN	DP	DFM	DBCD	TSS
	2689.933	103.179	32.258	938.015	224.265	500.000	111.582	200.000
S19.	Q	SOC	SNBC	SON	SOP	SFM	SBCD	VSS
	0.123	69.418	69.216	6.913	0.761	50.301	38.070	149.698
	ALK	DOC	DNBC	DN	DP	DFM	DBOD	TSS
	888.286	92.762	41.622	537.069	74.322	499.999	65.158	199.999
S25.	Q	SOC	SNBC	SON	SOP	SFM	SBCD	VSS
	9.996	5.471	2.121	0.818	0.054	1.750	6.581	13.022
	ALK	DOC	DNBC	DN	DP	DFM	DBOD	TSS
	257.811	14.797	11.374	23.349	5.380	500.000	6.400	14.773

PROCESS CHARACTERISTICS

CCOST = CAPITAL COST, DOLLARS
COSTO = OPERATING + MAINTENANCE COST, CENTS/1000 GAL.
ACOST = AMORTIZATION COST, CENTS/1000 GAL.
TCOST = TOTAL TREATMENT COST, CENTS/1000 GAL.

1	RAW WASTEWATER PUMPING	HEAD					CCOST	COSTO	ACOST	TCOST	ECF
		30.00					346951.	0.310	0.743	1.053	1.00
2	PRELIMINARY TREATMENT	IPREL					CCOST	COSTO	ACOST	TCOST	ECF
		1.0					144986.	0.412	0.310	0.723	1.00
3	PRIMARY SETTLER	FRPS	URPS	HPWK	GPS	APS	PGPM				
		0.50	400.0	14.0	1375.2	8.612	105.				
							CCOST	COSTO	ACOST	TCOST	ECF
						SETTLER	179840.	0.177	0.385	0.562	1.17
						SLUDGE PUMPS	58579.	0.202	0.125	0.328	1.00
4	AERATOR-FINAL SETTLER	BOD	MLSS	DEGC	CAER20	DO	AEFF20	URSS	GSS	HEAD	
		13.0	2000.	20.00	1.00	1.00	0.05	5.00	700.00	30.00	
		BOD2	DUSAT	XRSS	AFS	CAER	CEDR	VAER	VNIT	MLASS	MLBSS
		129.4	10.7	0.0074	20.85	1.00	0.124	2.151	2.521	671.	536.
		MLNBSS	MLDSS	MLISS	FOOD	RTURN	CNIT	ARCFD	BSIZE	CFPGL	QR
		507.	44.	236.	90.2	0.233	0.321	7489177.	5200.	0.74	2.365
							CCOST	COSTO	ACOST	TCOST	ECF
						AERATOR	376945.	0.000	0.807	0.807	1.14
						BLOWER	259038.	1.018	0.555	1.574	1.00
						SLUDGE PUMPS	64275.	0.158	0.137	0.296	1.00
						FINAL SETTLER	343730.	0.313	0.736	1.049	1.17
5	AEROBIC DIGESTION	XL	XAFS	DTA	TSS1	TSS2	BOD2	GSS	HEAD		
		4.	1.	10.0	25000.	200.	100.0	100.00	20.00		
		VAER	ACFM	OPUMP	AFS						
		190.692	7109.	0.17	1.72						
							CCOST	COSTO	ACOST	TCOST	ECF
						AERATOR	264511.	0.000	0.566	0.566	1.00
						BLOWER	324931.	1.129	0.696	1.826	1.20
						SLUDGE PUMPS	26762.	0.084	0.057	0.141	1.00
						FINAL	69630.	0.070	0.149	0.219	1.50

SETTLER

6	ANAEROBIC DIGESTER	TD	TDIG	C1DIG	C2DIG	VDIG	CH4	CO2			
		15.0	30.0	0.233	1154.	33.	60558.	31803.			
							CCOST	COSTO	ACOST	TCOST	ECF
							200746.	0.170	0.430	0.601	1.33
7	VACUUM FILTER	VFL	HPWK	TSS	IVACF	FECL3	WP	AVF			
		4.90	35.	200.	1.00	14.75	76.4	1326.5			
							CCOST	COSTO	ACOST	TCOST	ECF
							1052498.	1.041	2.255	3.297	1.00
8	MULTIPLE HEARTH INCINERATION	ML	NINC	HPWK	SPER	WV	HV	TYPE	EC	FC	CNG
		2.0	1.0	35.0	5.0	0.0	10000.0	1.0	0.01	0.14	0.97
		FHA	WFYR	PSDD	ECOST	FCOST	CCOST	COSTO	ACOST	TCOST	ECF
		944.	267527.	8800.	1155.	5006.	501316.	0.589	1.074	1.664	1.02
9	CHLORINATION	DCL2	TCL2				CCOST	COSTO	ACOST	TCOST	ECF
		8.0	30.0			FEED SYSTEM	75156.	0.599	0.161	0.760	1.00
						CONTACT BASIN	66620.	0.000	0.142	0.142	1.00
	ADMINISTRATIVE AND LABORATORY						CCOST	COSTO	ACOST	TCOST	
							148299.	0.410	0.317	0.728	
	GARAGE AND SHOP						CCOST	COSTO	ACOST	TCOST	
							43886.	0.000	0.094	0.094	
	LABORATORY OPERATION	XLAB					CCOST	COSTO	ACOST	TCOST	
		1.0					0.	0.473	0.000	0.473	
	YARDWORK OPERATION						CCOST	COSTO	ACOST	TCOST	
							0.	0.257	0.000	0.257	

TOTAL PLANT COST

TOTAL CAPITAL COST = 4548705. DOLLARS

TOTAL AMORTIZATION COST = 9.748 CENTS/1000 GAL.

TOTAL O + M COST = 7.420 CENTS/1000 GAL.

TOTAL TREATMENT COST = 17.169 CENTS/1000 GAL.

CCI	WPI	RI	YRS	OHR	PCT	DA	CCINT	XLAB	CKWH
1.506	1.122	0.060	25.0	3.50	0.150	1000.	0.06	1.00	0.013

RATIO	TCAP	YARD	TCC	XLAND	ENG	SUBT1	FISC	SUBT2	XINT
1.338	3399282.	475899.	3875175.	19976.	341777.	4236924.	32747.	4269675.	279024.

ACRE	AF
19.97	0.07822

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12. Eilers, R. G., Smith, R., "Executive Digital Computer Program for Preliminary Design of Wastewater Treatment Systems," November, 1970

APPENDIX

In developing a model for aerobic digestion, the ideal approach is to compute the volatile solids destruction based on mass balance and rate relationships. Although existing performance data do not adequately support this approach to the problem, an attempt will be made here to examine the feasibility of such an approach. Three cases will be considered. First, the simple fill and draw case where the reactor is filled with undigested sludge at time zero and then aerated for a number of days. The second case is the simple flow through reactor with a given volume of sludge being added continuously and an equal volume of digested sludge being removed continuously. The third case is shown diagrammatically in Figure 1 of the body of the report. Here, undigested sludge is added continuously and an equal volume of supernatant is removed continuously, but the solids are separated from the supernatant by means of a settler. It will be shown that sludge retention time is the significant parameter and when a settler is used, an SRT greater than the hydraulic detention time can be achieved.

In the body of this report it was shown that both primary and waste activated sludge is composed of inorganic material and organic or volatile material. Part of the volatile material is essentially nonbiodegradable. It will be assumed here that the biodegradable volatile material (both dissolved and particulate) is first converted to microorganisms in a negligable amount of time and that the microorganisms then are destroyed at a rate often called the endogenous respiration rate. It should also be noted that

microorganisms are composed of 18.5% nonbiodegradable material and 81.5% biodegradable material. The rate constant which applies to the biodegradable fraction of microorganisms can be represented by the following equation:

$$k_e = 0.10188*(1.047)^{T-20}$$

T = water temperature, degrees C

k_1 = endogenous respiration rate constant, $days^{-1}$

First, consider the simple fill and draw arrangement. If we let X_o equal the concentration of biodegradable solids in the feed sludge and X_e equal the concentration of biodegradable solids in the digested sludge, the following relationship can be used to estimate the fraction of the biodegradable volatile solids destroyed after t days:

$$X_e = X_o\, e^{-k_e t} \qquad (1)$$

Next, consider the simple flow through reactor. The following mass balance equation can be written for biodegradable volatile solids:

$$V(dX_e/dt) = Q(X_o - X_e) - k_e V X_e = 0 \qquad (2)$$

This equation can readily be solved with the following result:

$$X_e/X_o = 1/(1 + k_e*DT) \qquad (3)$$

In these equations, V is the volume of the aerator, Q is the volume flow through the aerator, and DT is the detention time (V/Q). The symbol (*) is used to indicate multiplication.

Equations (1) and (3) are shown plotted on semi-log paper in Figure 1A. for T = 20°C. Since t in equation (1) is the same as detention time (DT), we see that the fill and draw reactor is essentially more efficient than the flow through reactor.

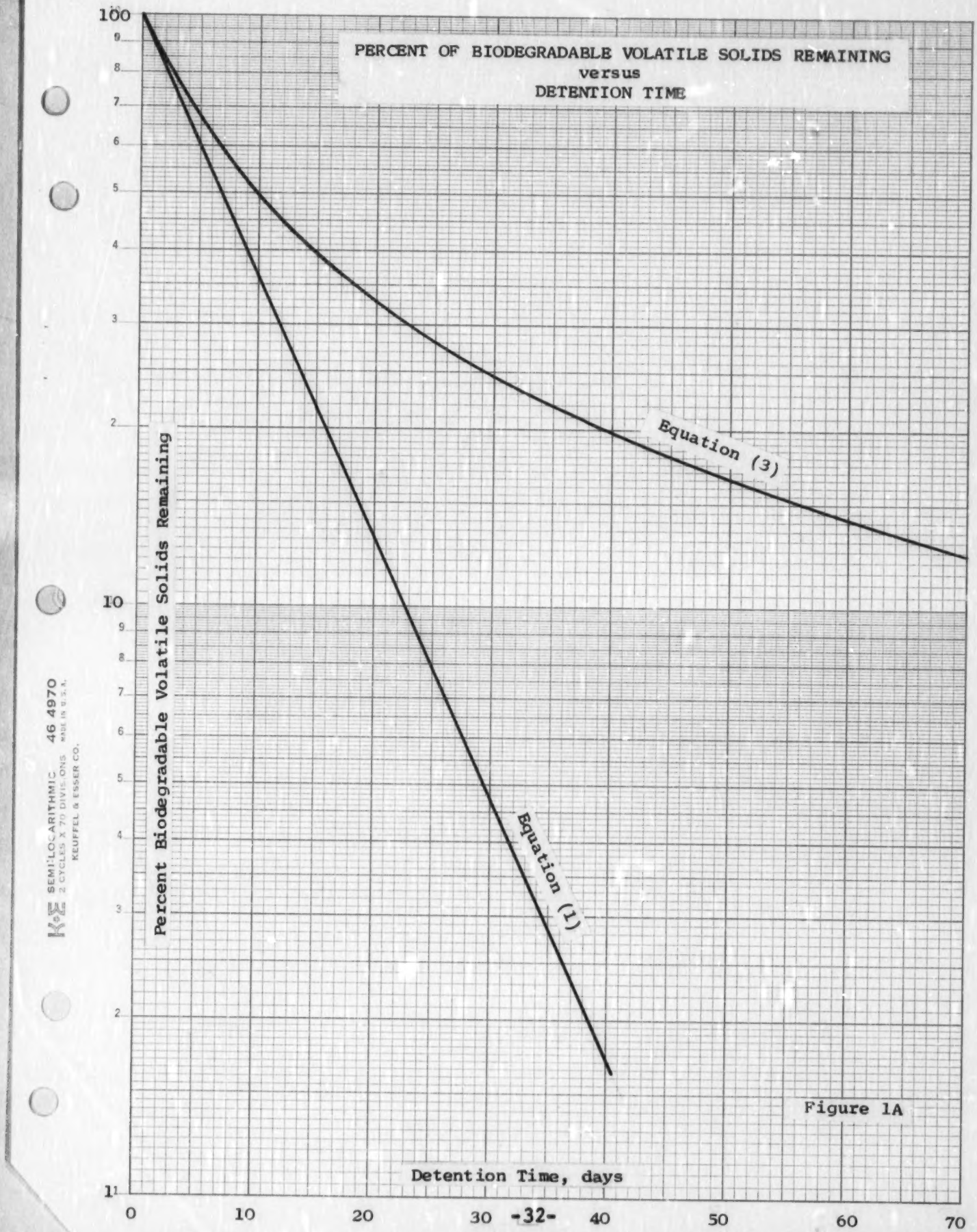
PERCENT OF BIODEGRADABLE VOLATILE SOLIDS REMAINING
versus
DETENTION TIME
Percent Biodegradable Volatile Solids Remaining
Detention Time, days
Equation (3)
Equation (1)
100
10
1
0
10
20
30
40
50
60
70
SEMILOGARITHMIC 46 4970
2 CYCLES X 70 DIVISIONS MADE IN U.S.A.
KEUFFEL & ESSER CO.

Figure 1A

The final case to be considered is the aerator followed by a settler. This differs from the second case only in that the sludge wasting from the aerobic digester is controlled. To express this control, define the term F_w as the actual mass of biodegradable volatile solids wasted per day, divided by the wasting rate for the simple flow through reactor, that is, QX_e. Thus, F_w is expressed by the following relationship:

$$F_w = \frac{(1/SRT)VX_e}{QX_e} = DT/SRT \qquad (4)$$

Sludge retention time (SRT) is defined as the mass of biodegradable solids in the aerator divided by the wasting rate for biodegradable solids. The dimension for SRT is days. Thus, we see that SRT must always exceed or equal DT. When the simple flow through reactor is considered, SRT equals DT. Notice also that the fraction of biodegradable solids remaining, when a settler is provided, is equal to F_wX_e/X_o. Equation (3) can be written for the case using the final settler and solved with the following result:

$$\text{Fraction remaining} = F_wX_e/X_o = 1/(1 + k_e*SRT) \qquad (5)$$

For the second and third cases, therefore, the best parameter is SRT because SRT = DT for the case with no settler.

Now it is possible to see how these concepts agree with reported data. Lawton and Norman[8] reported a relationship between percent reduction of volatile solids and sludge age. This relationship is shown in Figure 2A. The sludge used by Lawton and Norman was a mixture of primary and waste activated sludge. Sludge age is defined

K+E SEMI-LOGARITHMIC 46 4970
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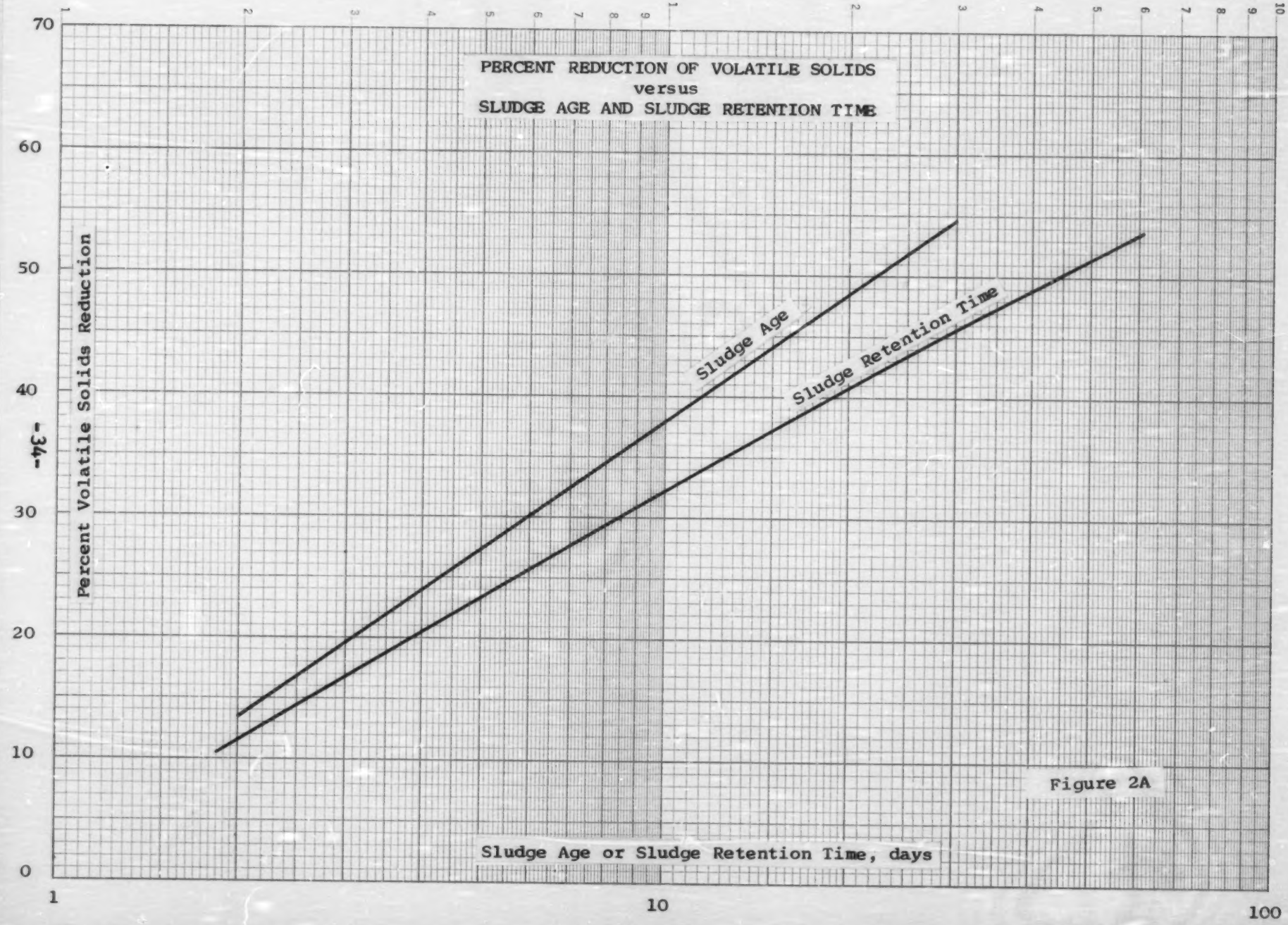

Figure 2A

as the mass of volatile solids in the aerator divided by the mass of sludge added per day. Since the relationship between sludge age and SRT is known, the relationship reported by Lawton and Norman can be expressed as a function of SRT. This relationship is also shown in Figure 2A. Notice that these relationships apply to all volatile solids, not just biodegradable solids.

In Figure 3A, the solid lines represent equation (5) for three water temperatures. Notice that these lines are not straight but tend to become flat at the large values for SRT. The data reported by Jaworski et al.[1], using simple flow through reactors of bench scale, were interpreted in the following way: the maximum percent reduction reported by Jaworski, using a mixture of primary and waste activated sludge, was 46%. It was assumed that 90% of the biodegradable solids had been degraded and the Jaworski data is shown plotted by the points with circles, squares and triangles, representing different water temperatures. The data shown in Figure 3A are for biodegradable solids, however, and the discrepancy is therefore not excessive. For example, if we assume that about 50% of the solids were biodegradable, at 20°C Jaworski would have predicted about 80% removal of biodegradable solids at 15 days SRT. This is equivalent to 40% removal of volatile solids. Using the theoretical approach at 15 days SRT, the removal of volatiles would have been 31% removal of volatile solids. At 15°C, Jaworski would have predicted 35% reduction of VSS and the theoretical equations would have predicted 28% reduction at a SRT of 15 days. The relationship given by Lawton and Norman is shown by the dashed line in Figure 3A, assuming that

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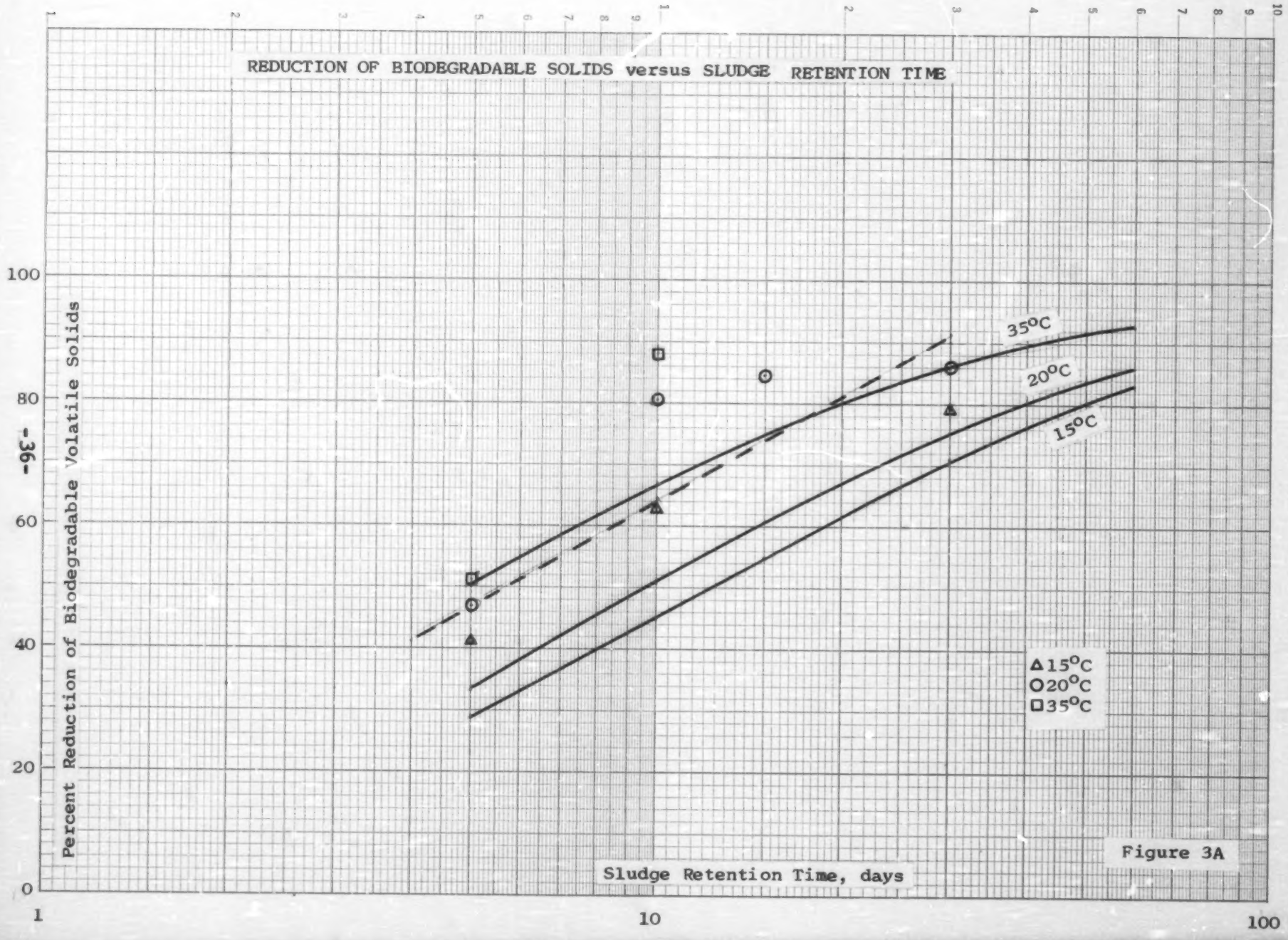

Figure 3A

50% of the volatile solids were biodegradable. This line would predict 37% reduction of VSS at 15 days SRT. Lawton did not give a dependence on temperature.

In general, we see that the theoretical approach predicts a smaller fractional removal of biodegradable volatile solids than that reported by Jaworski and Lawton from bench scale studies.

Some recent results from the Metro Denver plant show a 44.8% reduction in VSS when waste activated sludge alone is digested aerobically. The SRT was 13.4 days and the detention time was 8.57 days. The water temperature averaged 22°C.

The theoretical model would have predicted a 60% reduction of biodegradable volatile solids. If we assume that the volatile solids are 38% biodegradable as shown in Figure 4 of the body of the report, the reduction in VSS would have been only 23%. Again, the available data on performance of the aerobic digester tends to show greater destruction of volatiles than that predicted by the theory. Until the theory can be shown to conform with experimental results, the model will be based on the concepts given in the body of this report.

A short computer program has been developed to study the fill and draw kind of operation normally seen in smaller plants. The definition of terms used in this program is given in Table 1A. A listing of the program with sample printout is attached. The printout shows the pounds of each class of solids wasted from the digester at the end of each digester cycle. The logic used in writing the program can be seen from study of the program.

DEFINITIONS OF COMPUTER SYMBOLS

Computer Symbol Used	Definition and Nominal Value
DT	detention time, days = VAER/Q1 15 days
Q1	volume of undigested sludge stream, mgd 0.0117 at 1 mgd
TSS	concentration of solids in digester just before wasting 25,000 mg/l
RW	mass of sludge in digester just prior to wasting/mass of sludge wasted, 2-3
FIS	fraction of sludge in digester just prior to wasting which is inorganic, .35
FVS	fraction of sludge in digester jus prior to wasting which is volatile, .65
FBS	fraction of volatile sludge in digester just prior to wasting which is biodegradable, 0.1
MLISS	concentration of inorganic solids in feed stream, mg/l 1297 mg/l
MLNBS	concentration of nonbiodegradable volatile solids in feed stream, mg/l 4183 mg/l
MLBSS	concentration of biodegradable solids in feed stream, mg/l 4520 mg/l
CEDR	endogenous respiration rate constant which applies to biodegradable solids, 0.10188 day^{-1} at $20^{o}C$
VAER	volume of aerobic digester, mg, DT*Q1
WMAX	mass of solids in digester just prior to wasting, lbs.
WTSS	mass of solids in digester, lbs.
WVSS	mass of volatile solids in digester, lbs.
WNBS	mass of nonbiodegradable volatile solids in digester, lbs.
WBSS	mass of biodegradable volatile solids in digester, lbs.
T	time after wasting, days

TABLE 1A

The fill and draw type of aerobic digester normally used in small plants can also be analyzed by means of mass balances and rate equations. For example, assume that either waste activated sludge or a mixture of primary and WAS is fed to the digester once a day. About once or twice a week the sludge is allowed to settle and supernatant is drawn off. When the sludge becomes too thick to settle, digested sludge is wasted from the aerobic digester. Assume that we know this limiting concentration and call this concentration TSS, mg/l. The amount of sludge in the digester when wasting is started is therefore, Q*DT*TSS*8.33. Here Q is the feed sludge added per day, mgd and DT is the detention time, days.

The solids in the aerator, when the time to waste is reached, will be made up of inorganic solids (WISS) organic nonbiodegradable solids (WNBS) and biodegradable volatile solids (WBSS). These symbols stand for the pounds of these classes of solids in the digester when wasting is started. Normally only a fraction of the contents of the aerobic digester are wasted and the ratio of total solids in the digester to the amount wasted will be called RW.

When equilibrium is reached for the fill and draw aerator, the amount of inert solids wasted, both organic and inorganic, must just equal the amount which entered the digester since the last wasting cycle. This can be expressed as follows:

$$WISS/RW = MLISS*Q*8.33*T \quad (6)$$

$$WNBS/RW = MLNBS*Q*8.33*T \quad (7)$$

In these equations, MLISS is the concentration of inorganic solids and MLNBS is the concentration of volatile nonbiodegradable solids in the feed. The time between wasting points is T days in the above equations. If we let WBSS equal the poinds of biodegradable solids in the aerobic digester just prior to wasting, WBSS can be expressed as follows:

$$WBSS = WBSS*(RW - 1)/RW*e^{-k_e T} + Q*MLBSS*8.33* [e^{-k_e} + e^{-k_e 2} \ldots e^{-k_e T}] \quad (8)$$

Let the sum of the exponential functions included in the squares parentheses be called F(T)*T. The function F(T) is shown in Table 2A for various values of k_e. Equation (8) can then be written in the following form:

$$WBSS = WBSS*(RW-1)/RW*e^{-k_e T} + Q*MLBSS*8.33*F(T)*T \quad (9)$$

This equation can now be solved for the amount of biodegradable solids wasted per wasting cycle (WBSS/RW) as follows:

$$WBSS/RW = Q*MLBSS*8.33*F(T)*T/(RW - (RW-1)\ e^{-k_e T}) \quad (10)$$

The following equation can now be written for the solids present in the digester just prior to wasting:

$$Q*DT*TSS*8.33 = WISS + WNBS + WBSS \quad (11)$$

Equations (6), (7), and (10) can now be substituted into equation (11) with the following results:

$$DT/RW/T = (MLISS/TSS) + (MLNBS/TSS) + (MLBSS/TSS)*F(T)/(RW - (RW-1)\ e^{-k_e T}) \quad (12)$$

The function F(T) for 20°C is shown plotted in Figure 4A

TABLE 2A

T	VALUES OF FUNCTION F(T)										
	0.06	0.08	0.10	0.12	0.14	0.16	0.18	0.20	0.22	0.24	k_e, day^{-1}
1	0.9417	0.9231	0.9048	0.8869	0.8693	0.8521	0.8352	0.8187	0.8025	0.7866	
2	0.9143	0.8876	0.8617	0.8367	0.8125	0.7891	0.7664	0.7445	0.7232	0.7027	
3	0.8879	0.8539	0.8214	0.7904	0.7607	0.7323	0.7052	0.6792	0.6544	0.6307	
4	0.8626	0.8220	0.7836	0.7475	0.7133	0.6810	0.6506	0.6217	0.5945	0.5687	
5	0.8382	0.7916	0.7482	0.7077	0.6699	0.6347	0.6018	0.5710	0.5422	0.5152	
6	0.8148	0.7628	0.7150	0.6709	0.6302	0.5927	0.5581	0.5260	0.4963	0.4688	
7	0.7923	0.7354	0.6838	0.6367	0.5938	0.5546	0.5188	0.4861	0.4560	0.4285	
8	0.7706	0.7094	0.6544	0.6050	0.5604	0.5201	0.4836	0.4505	0.4205	0.3932	
9	0.7497	0.6847	0.6269	0.5755	0.5296	0.4886	0.4518	0.4188	0.3891	0.3623	
10	0.7296	0.6611	0.6010	0.5480	0.5013	0.4599	0.4232	0.3905	0.3613	0.3352	
11	0.7103	0.6387	0.5766	0.5225	0.4752	0.4337	0.3973	0.3651	0.3365	0.3112	
12	0.6916	0.6174	0.5537	0.4987	0.4511	0.4098	0.3738	0.3422	0.3144	0.2899	
13	0.6737	0.5971	0.5320	0.4765	0.4289	0.3879	0.3524	0.3216	0.2946	0.2710	
14	0.6564	0.5777	0.5116	0.4558	0.4083	0.3678	0.3330	0.3029	0.2769	0.2541	
15	0.6397	0.5593	0.4924	0.4364	0.3893	0.3493	0.3153	0.2861	0.2609	0.2390	
16	0.6237	0.5417	0.4742	0.4183	0.3716	0.3323	0.2991	0.2707	0.2464	0.2254	
17	0.6082	0.5250	0.4571	0.4013	0.3552	0.3166	0.2842	0.2568	0.2333	0.2131	
18	0.5933	0.5089	0.4409	0.3854	0.3399	0.3022	0.2706	0.2440	0.2214	0.2020	
19	0.5789	0.4937	0.4255	0.3705	0.3257	0.2888	0.2581	0.2324	0.2106	0.1920	
20	0.5650	0.4791	0.4110	0.3565	0.3124	0.2764	0.2465	0.2216	0.2006	0.1828	
21	0.5516	0.4651	0.3973	0.3434	0.3001	0.2649	0.2359	0.2118	0.1916	0.1744	
22	0.5387	0.4518	0.3843	0.3310	0.2885	0.2542	0.2260	0.2027	0.1832	0.1667	
23	0.5262	0.4391	0.3719	0.3194	0.2777	0.2442	0.2169	0.1944	0.1755	0.1596	
24	0.5141	0.4269	0.3602	0.3084	0.2676	0.2349	0.2084	0.1866	0.1684	0.1531	
25	0.5025	0.4152	0.3491	0.2981	0.2581	0.2263	0.2005	0.1794	0.1618	0.1471	
26	0.4912	0.4041	0.3385	0.2883	0.2492	0.2182	0.1932	0.1727	0.1557	0.1415	
27	0.4804	0.3934	0.3284	0.2791	0.2408	0.2106	0.1863	0.1665	0.1501	0.1363	
28	0.4699	0.3831	0.3189	0.2703	0.2329	0.2034	0.1799	0.1607	0.1448	0.1315	
29	0.4597	0.3733	0.3098	0.2621	0.2255	0.1968	0.1739	0.1552	0.1398	0.1270	
30	0.4499	0.3639	0.3011	0.2543	0.2184	0.1905	0.1682	0.1501	0.1352	0.1227	
31	0.4404	0.3548	0.2929	0.2468	0.2118	0.1846	0.1629	0.1454	0.1309	0.1188	
32	0.4312	0.3462	0.2850	0.2398	0.2055	0.1790	0.1579	0.1409	0.1268	0.1151	
33	0.4223	0.3378	0.2775	0.2331	0.1996	0.1737	0.1532	0.1366	0.1230	0.1116	
34	0.4137	0.3298	0.2703	0.2267	0.1940	0.1687	0.1488	0.1326	0.1194	0.1083	
35	0.4054	0.3221	0.2634	0.2207	0.1887	0.1640	0.1446	0.1289	0.1160	0.1053	
36	0.3974	0.3147	0.2569	0.2149	0.1836	0.1595	0.1406	0.1253	0.1128	0.1023	
37	0.3896	0.3076	0.2506	0.2094	0.1788	0.1553	0.1368	0.1219	0.1097	0.0996	
38	0.3820	0.3008	0.2446	0.2042	0.1742	0.1513	0.1332	0.1187	0.1069	0.0970	
39	0.3747	0.2942	0.2388	0.1992	0.1699	0.1474	0.1298	0.1157	0.1041	0.0945	
40	0.3676	0.2879	0.2333	0.1944	0.1657	0.1438	0.1266	0.1128	0.1015	0.0921	
41	0.3607	0.2818	0.2280	0.1899	0.1617	0.1403	0.1235	0.1101	0.0991	0.0899	
42	0.3540	0.2759	0.2229	0.1855	0.1579	0.1370	0.1206	0.1075	0.0967	0.0877	
43	0.3475	0.2702	0.2181	0.1813	0.1543	0.1338	0.1178	0.1050	0.0944	0.0857	
44	0.3413	0.2648	0.2134	0.1773	0.1509	0.1308	0.1151	0.1026	0.0923	0.0837	
45	0.3352	0.2595	0.2089	0.1735	0.1476	0.1279	0.1126	0.1003	0.0903	0.0819	
46	0.3293	0.2544	0.2046	0.1698	0.1444	0.1252	0.1102	0.0981	0.0883	0.0801	
47	0.3235	0.2495	0.2004	0.1662	0.1413	0.1225	0.1078	0.0960	0.0864	0.0784	
48	0.3179	0.2447	0.1964	0.1628	0.1384	0.1200	0.1056	0.0940	0.0846	0.0768	
49	0.3125	0.2401	0.1926	0.1596	0.1356	0.1175	0.1034	0.0921	0.0829	0.0752	
50	0.3073	0.2357	0.1888	0.1564	0.1329	0.1152	0.1013	0.0903	0.0812	0.0737	
51	0.3022	0.2314	0.1853	0.1534	0.1303	0.1129	0.0994	0.0885	0.0796	0.0722	
52	0.2972	0.2272	0.1818	0.1505	0.1278	0.1108	0.0975	0.0868	0.0781	0.0708	
53	0.2924	0.2232	0.1785	0.1477	0.1254	0.1087	0.0956	0.0852	0.0766	0.0695	
54	0.2877	0.2193	0.1752	0.1450	0.1231	0.1067	0.0938	0.0836	0.0752	0.0682	
55	0.2831	0.2156	0.1721	0.1424	0.1209	0.1047	0.0921	0.0821	0.0738	0.0670	
56	0.2787	0.2119	0.1691	0.1398	0.1187	0.1029	0.0905	0.0806	0.0725	0.0658	
57	0.2744	0.2084	0.1662	0.1374	0.1167	0.1010	0.0889	0.0792	0.0712	0.0646	
58	0.2702	0.2050	0.1634	0.1351	0.1146	0.0993	0.0874	0.0778	0.0700	0.0635	
59	0.2661	0.2016	0.1607	0.1328	0.1127	0.0976	0.0859	0.0765	0.0688	0.0624	
60	0.2621	0.1984	0.1580	0.1306	0.1108	0.0960	0.0845	0.0752	0.0677	0.0614	

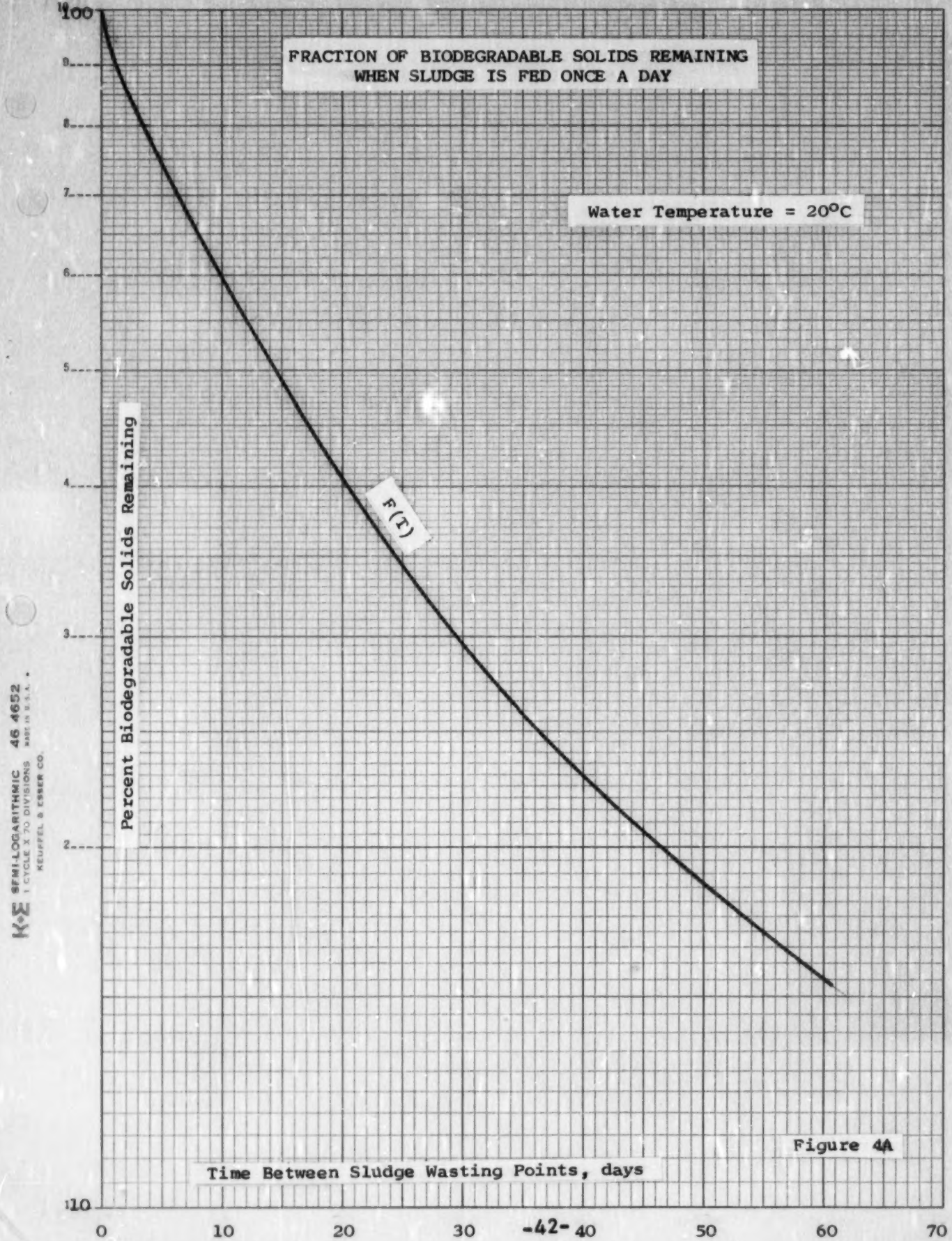
FRACTION OF BIODEGRADABLE SOLIDS REMAINING
WHEN SLUDGE IS FED ONCE A DAY
Water Temperature = 20°C
F(T)
Percent Biodegradable Solids Remaining
Time Between Sludge Wasting Points, days
100
9
8
7
6
5
4
3
2
1
0
10
20
30
40
50
60
70

Figure 4A

The fraction of volatile solids destroyed can now be expressed as follows:

$$\text{Fraction VSS Removed} = (1 - F(T)/(RW - (RW-1)e^{-k_e T})/(MLNBS/MLBSS) + 1) \quad (13)$$

Thus, the conclusion is that the period between wasting should be as long as possible and when wasting occurs as small a fraction of the sludge should be wasted as possible.

To show how the equations developed can be used, assume the following values for feed sludge:

$$Q = 0.0117$$
$$MLBSS = 4520 \text{ mg/l}$$
$$MLNBS = 4183 \text{ mg/l}$$
$$MLISS = 1297 \text{ mg/l}$$
$$k_e = 0.10188 \text{ day}^{-1}$$

Now assume that 50% of the sludge will be wasted every 15 days. Also, take the limiting concentration of sludge in the digester as 25,000 mg/l. By use of equation (13), we compute that 38% of the volatile solids will be destroyed. Equation (12) can now be used to compute the required detention time of 8.05 days. If we had designed to waste 50% of the sludge every 30 days, the destruction of volatile solids would have been 44.1% and the required detention time would have been 14.8 days.

The intermittent feeding kind of analysis can also be applied to the bench scale data reported by Jaworski and others. If this is done, the rates of removal achieved by Jaworski, as compared to that predicted by the theory, seem faster than they did when compared to the simple flow through theory. Clearly, there is a need for well controlled full scale experiments with aerobic digestion.

```
      REAL MLBSS,MLNBS,MLISS
      IN=2
      IO=5
      READ(IN,1)  DT,Q1,TSS,RW,FBS,FIS,FVS,MLBSS,MLNBS,MLISS,CEDR
    1 FORMAT(8F10.4)
    2 FORMAT(1H1)
      WRITE(IO,2)
    7 FORMAT(3X,F4.1,2X,F6.4,2X,F7.0,2X,F4.1,2X,F4.2,2X,F4.2,2X,F4.2,2X,
     1F6.0,2X,F6.0,2X,F6.0,2X,F7.5,////)
    8 FORMAT(4X,'DT',5X,'Q1',6X,'TSS',5X,'RW',4X,'FBS',3X,'FIS',2X,
     1'FVS',3X,'MLBSS',3X,'MLNBS',3X,'MLISS',3X,'CEDR',/)
      WRITE(IO,8)
      WRITE(IO,7)  DT,Q1,TSS,RW,FBS,FIS,FVS,MLBSS,MLNBS,MLISS,CEDR
      VAER=DT*Q1
      WMAX=TSS*VAER*8.33
      WTSS=WMAX*(RW-1.)/RW
      WISS=WTSS*FIS
      WVSS=WTSS*FVS
      WBSS=WVSS*FBS
      WNBS=WVSS-WBSS
      WRITE(IO,9)
    9 FORMAT(30X,'AMOUNTS WASTED',/,11X,'T',8X,'WTSS',10X,'WBSS',8X,
     1'WNBS',9X,'WISS',/)
   50 T=0.0
  100 T=T+1.0
      WBSS=WBSS+Q1*MLBSS*8.33
      WISS=WISS+Q1*MLISS*8.33
      WNBS=WNBS+Q1*MLNBS*8.33
      WBSS=WBSS/EXP(CEDR)
      WTSS=WISS+WBSS+WNBS
      IF(WTSS-WMAX)  100,200,200
  200 WTSS=WTSS/RW
      WISS=WISS/RW
      WBSS=WBSS/RW
      WNBS =WNBS /RW
      WRITE(IO,10)  T,WTSS,WBSS,WNBS ,WISS
   10 FORMAT(5X,F8.1,3X,F12.0,3X,F8.1,3X,F12.0,3X,F8.1)
      WTSS=WTSS*(RW-1.)
      WISS=WISS*(RW-1.)
      WNBS=WNBS*(RW-1.)
      GO TO 50
  500 CONTINUE
      CALL EXIT
      END
```

DT	Q1	TSS	RW	FBS	FIS	FVS	KLBSS	KLNBS	KLISS	CEOR
15.0	0.0117	25000.	4.0	0.10	0.35	0.65	4520.	4183.	1297.	0.10188

T	WTSS	AMOUNTS WASTED WBSS	WNBS	WISS
14.0	9163.	887.2	5435.	2840.8
16.0	9212.	869.1	5707.	2636.2
16.0	9262.	868.2	5911.	2482.8
15.0	9149.	851.1	5962.	2336.1
16.0	9227.	867.3	6102.	2257.7
16.0	9274.	868.1	6207.	2198.9
15.0	9158.	851.1	6184.	2123.2
16.0	9234.	867.3	6269.	2098.0
16.0	9279.	868.1	6332.	2079.1
15.0	9162.	851.1	6278.	2033.3
16.0	9237.	867.3	6339.	2030.6
16.0	9281.	868.1	6385.	2028.6
15.0	9164.	851.1	6317.	1995.4
16.0	9238.	867.3	6368.	2002.2
16.0	9282.	868.1	6407.	2007.3
15.0	9165.	851.1	6334.	1979.5
16.0	9239.	867.3	6381.	1990.2
16.0	9283.	868.1	6416.	1998.3
15.0	9165.	851.1	6341.	1972.7
16.0	9239.	867.3	6386.	1985.1
16.0	9283.	868.1	6420.	1994.5
15.0	9165.	851.1	6344.	1969.9
16.0	9239.	867.3	6388.	1983.0
16.0	9283.	868.1	6422.	1992.9
15.0	9165.	851.1	6345.	1968.7
16.0	9239.	867.3	6389.	1982.1
16.0	9283.	868.1	6423.	1992.2
15.0	9165.	851.1	6346.	1968.2
16.0	9239.	867.3	6390.	1981.7
16.0	9283.	868.1	6423.	1991.9
15.0	9165.	851.1	6346.	1967.9
16.0	9239.	867.3	6390.	1981.6
16.0	9283.	868.1	6423.	1991.8
15.0	9165.	851.1	6346.	1967.9
16.0	9239.	867.3	6390.	1981.5
16.0	9283.	868.1	6423.	1991.7
15.0	9165.	851.1	6346.	1967.8
16.0	9239.	867.3	6390.	1981.5
16.0	9283.	868.1	6423.	1991.7
15.0	9165.	851.1	6346.	1967.8
16.0	9239.	867.3	6390.	1981.5
16.0	9283.	868.1	6423.	1991.7
15.0	9165.	851.1	6346.	1967.8
16.0	9239.	867.3	6390.	1981.5
16.0	9283.	868.1	6423.	1991.7
15.0	9165.	851.1	6346.	1967.8
16.0	9239.	867.3	6390.	1981.5